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THE EVOLUTION OF THE STARS AND THE FORMATION OF THE EARTH. II

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Evidence in Support of Sequence Proposed

THERE are several lines of evidence in support of the *order* of evolution which we have outlined.

1. The close relationship of the bright-line nebular spectrum, the bright-line stellar spectrum and the spectra of the simplest helium stars; the practically continuous sequence of spectra from the helium stars to the red stars.

2. In the long run, we must expect the stars to grow colder, at least as to the surface strata. What the average interior temperatures are is another question; the highest interior temperatures are thought to be reached at an intermediate or quite late stage in the process, in accordance with principles investigated by Lane and others; but the temperatures existing in the deep interiors seem to have little direct influence in defining the spectral characters of the stars, which are concerned more directly with the surface strata.[7] We should therefore expect the simpler types of spectra, such as we find in the helium and hydrogen stars, in the early stages of the evolutionary process. The complicated spectra of the metals, and particularly the oxides of the metals, should be in evidence late in stellar life, when the atmospheres of the stars have become denser and colder.

3. The velocities of the Orion nebula, the Trifid nebula, the Carina nebula, and of several other irregular nebulæ, have been measured with the spectroscope. These bodies seem to be nearly at rest with reference to the stellar system. The helium stars have the lowest-known stellar velocities, and the average velocities of the stars are higher and higher as we pass from the helium stars, through the hydrogen and solar stars, up to the red stars. The average velocities of the brighter stars of the different spectral classes, as determined with the D. O. Mills spectrographs at Mount Hamilton and in Chile, are as in the following table:

Spectral Class	No. of Stars	Average Velocity in Space
B	225	12.9 km. per sec.
A	177	21.9
F	185	28.7
G	128	29.9
K	382	33.6
M	73	34.3

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[7] This important point seems not to have been realized by all theorists.

We can not place the irregular nebulæ after the red stars: their velocities are too small, and their spectra have no resemblances to the red-star spectra.

4. Wherever we find large irregular gaseous nebulæ we find stars in the early subdivisions of the helium group. They are closely related in position. This is true of the Orion and other similar regions. The irregular, gaseous nebulæ are in general found in and near the Milky Way, and so are the helium stars. The yellow and red stars, at least the brighter ones, do not cluster in nebulous regions.

5. The stars are more and more uniformly distributed over the sphere as one goes from the helium stars through the hydrogen and solar stars, to the red stars. The Class M stars show little or no preference for the Milky Way. Of course, I am speaking here of the brighter and nearer stars which we have been able to study by means of the spectroscope, and not at all of the faint stars which form the unstudied distant parts of the Milky Way structure. The helium stars are young, their motions are slow, and they have not wandered far from the place of their birth. Not so with the older stars.

6. The visual double stars afford strong evidence that the order of evolution described is correct. The 36-inch refractor has shown that one star in 18, on the average, brighter than the ninth visual magnitude, consists of two or more suns which we can not doubt are in slow revolution around each other. The number of double stars observable would be very much greater than this if they were not so far away. Of the 20 stars which we say are our nearest neighbors, 8 are well known double stars; one double in each two and one half, on the average. Aitken has made a specialty of observing the double stars whose components in each case are very close together and are in comparatively rapid revolution. His program includes 164 such systems whose types of spectra are known, as in the following table:

Spectrum	Number of Double Stars
Bright-line	0
Class B	4
Class A–F	31
Class G–N	28
Class M–N?	1

The message which this table brings is clear. The double stars whose spectra are of the Bright-Line and Class B varieties have their components so close together that only 4, of Class B, are visible. The great majority fall in Classes A to K; 159 out of 164. The component stars in these classes are far enough apart to be visible in the telescopes, and yet are close enough to be revolving in periods reasonably short. In the Class M double stars, this program contains not more than one star, and I believe the explanation is this: double stars of Class M are in general so far apart, and therefore their periods of revolution are so long, that they do not get upon programs of rapidly revolving stars. Also, the fainter components in many red stars must have cooled off so far that they are invisible. The distances between the components of visual double stars are in general the greater as we proceed from the helium stars through the various spectral classes up to Class M. There are reasons for believing that two stars revolving around their center of mass have gradually increased their distance apart, and therefore their revolution period. If this is true, the Classes G and K double stars are effectively older than Classes A and F double stars, and these in turn are effectively older than Class B double stars.

7. The spectrograph has great advantages over the telescope in discovering and observing double stars whose components are very close together, by virtue of the facts that the spectrograph measures velocities of approach and recession in absolute units—so many kilometers per second—and that the speeds of rotation in binary systems are higher the closer together the two components are. The observations of the brighter helium stars, especially those made at the Yerkes Observatory by Frost and Adams, have shown that one helium star in every two and one half on the average is a very close double. In β Cephei, an early Class B star, the components are so close that they revolve around each other in 4½ hours; many systems have periods in the neighborhood of a day, of two days, of three days, and so on. Similar observations made with the D. O. Mills spectrographs in both hemispheres have shown that about one star in every four of the bright stars, on the average, is a double star. In general, the proportion of spectroscopic doubles discovered to date is greatest in Class B and decreases as we proceed toward Class M. The explanation is simple: in the Class B doubles the components are close together, their orbital velocities are very high and change rapidly, and the spectrograph is able to discover the variations with little loss of time. As we pass toward the yellow and red spectroscopic binaries we find the components separated more and more, the orbital velocities are smaller and the periods longer, the variations of velocity are more difficult to discover, and in the wider pairs we must wait many years before the variations become appreciable. There is a very marked progression of the average lengths of periods of the spectrographic double stars as we pass from the Class B to the Class M pairs. Similarly, the eccentricities of the orbits of the binaries increase as we proceed in the same direction. Accumulating evidence is to the effect that the proportion of double stars to single stars may be as great in the Classes A to K as in Class B.

8. Kapteyn believes that he is able to divide the individual stars—those whose proper motions are known—into the two star streams

which he has described; and he finds that the first stream is rich in the early blue stars, less rich relatively in yellow stars, and poor in red stars, whereas the second stream is very poor in early blue stars, rich in yellows, and relatively very rich in reds. His interpretation is that the stream-one stars are effectively younger than the stream-two stars, on the whole. Stream one still abounds in youthful stars: they grow older and the yellow and red stars will then predominate. Stream two abounds in stars which were once young, but are now middle-aged and old.

The eight lines of argument outlined are in harmony to the effect that there is a sequence of development from nebulæ to red stars.

The extremely red stars are all faint, only a very few being visible to the naked eye, and these near the limit of vision. Our knowledge concerning them is relatively limited. That these, and all stars, will become invisible to our telescopes, and ultimately be dark unshining bodies, is the logical conclusion to which the evolutionary processes will lead. As I have already stated, both Newcomb and Kelvin were inclined to believe that the major part of gravitational matter in the universe is already invisible.

It should be said that a few astronomers doubt whether the order of evolution is so clearly defined as I have outlined it; in fact, whether we know even the main trend of the evolutionary process. We occasionally encounter the opinion that the subject is still so unsettled as not to let us say whether the helium stars are effectively young or the red stars are effectively old. Lockyer and Russell have proposed hypotheses in which the order of evolutionary sequence begins with comparatively cool red stars and proceeds through the yellow stars to the very hot blue stars, and thence back through the yellow stars to cool red stars.

I think the essentially unanimous view of astronomers is to the effect that the great mass of accumulated evidence favors the order of evolution which I have described. We are all ready to admit that there are apparent exceptions to the simple course laid down, but that these exceptions are revolutionary in effect, and not hopeless of removal, has not yet, in my opinion, been established.

PHYSICAL CONDITIONS GOVERN APPEARANCES OF SPECTRA

A question frequently asked is this: if the yellow and red stars have been developed from the blue stars, why do not the thousands of lines in the spectra of the yellow and red stars show in the spectra of the blue stars? Indeed, why do not the elements so conspicuously present in the atmosphere of the red stars show in the spectra of the gaseous nebulæ? The answer is that the conditions in the nebulæ and in the youngest stars are such that only the *simplest elements,* like hydrogen and helium, and in the nebulæ nebulium, which we think are nearest to the elemental state of matter, seem to be able to form or exist in them; and the temperature must lower, or other conditions change to the conditions existing in the older stars, before what we may call the more complicated elements can construct themselves out of the more elemental forms of matter. The oxides of titanium and of carbon found in the red stars, where the surface temperatures must be relatively low, would dissociate themselves into more elemental components and lose their identity if the temperature and other conditions were changed back to those of the early helium stars. Lockyer's name is closely connected with this phenomenon of dissociation. There is no evidence, to the best of my knowledge, that the elements known in our Earth are not essentially universal in distribution, either in the forms which the elements have in the Earth, or dissociated into simpler forms wherever the temperatures or other conditions make dissociations possible and unavoidable.

The meteorites, which have come through the atmosphere to the Earth's surface, contain at least 25 known terrestrial elements. That they have not been found thus far to contain all of our elements is not surprising, for we should have difficulty in finding a piece of our Earth weighing a few kilograms which would contain 25 of our elements. We have not found any elements in meteorites which are unknown to our chemists. Our comets, which ordinarily show the presence of not more than three elements, carbon, nitrogen and oxygen, give certain evidence of sodium in their composition when they approach fairly near to the Sun; and the great comet of 1882, when very close to the Sun, developed in its spectrum many bright lines not previously seen in comet spectra, which Copeland said were due to iron. That the comets do not show a greater number of elements is not in the least surprising: they are not condensed bodies, and we think that their average temperature is low, too low generally to develop the luminous vapors of the more refractory elements. If their temperatures, approximated those which exist in the stars, their spectra would probably reveal the presence of many of the elements which exist in the meteorites. Of course the proof of this is lacking.

DESTINY OF THE STELLAR SYSTEM

We have said that the evolutionary processes depend primarily upon the loss of heat. This is to the best of our knowledge a genuine loss, except as some of the heat rays happen to strike other celestial bodies. The flow of heat energy from a star must be essentially continuous, always in one direction from hotter bodies to colder bodies, or into so-called unending and heatless space. Temperatures throughout the universe are apparently moving toward uniformity, at the level of absolute zero. Now, this uniformity would mean universal stagnation and death. It is possible to have life and to do work only when there are differences of temperature between the bodies concerned: work is done or accompanied by a flow of heat, always from the hotter to the colder body. We are not aware that any compensating principle exists. Several students of the subject, notably Arrhenius, have searched for such a principle, a fountain of youth so to speak, in accordance with which the vigor of stellar life should maintain itself from the beginning of time to the end of time; but I think that nothing approaching a satisfactory theory has yet been formulated. The stellar universe seems, from our present point of view, to be slowly "running down." The processes will not end, however, when all the heat generable *within* the stars shall have been radiated into an endless space. Every body within the universe, it is conceivable, could have cooled down to absolute zero, but the system might still be in its youth. So long as the stars, whether intensely hot or free from all heat, are rotating rapidly on their axes or are rushing through space with high speeds, the system will remain *very much alive*. Collisions or very close approaches of two stars are bound to occur sooner or later, whether the stars are hot or cold, and in all such cases a large share of the kinetic energy—the energy of motion—of the two bodies will be converted into heat. A collision, under average stellar conditions, should convert the two stars into a luminous gaseous nebula, or two or more nebulæ, which would require hundreds or thousands of millions of years to evolve again into young stars, middle-aged stars, old stars, and stars absolutely cold. So long as any of these bodies retain motion with reference to other bodies, they retain the power of rebirth and another life. Not to go too far into speculative detail, the general effect of these processes would be the destruction of relative motions and the gradual decrease in the number of separate bodies, through coalescence. Assume further, however, that all existing bodies, widely scattered through the stellar system, are absolutely cold and absolutely at rest with reference to each other: the system might even then be only middle-aged. The mutual gravitations of the bodies would still be operative. They would pass each other closely, or collide, under high generated velocities: there would be new nebulæ, and new and vigorous stellar life to continue through other long ages. The system would not run down until all the kinetic energy had been converted into heat, and all the heat generable had been dissipated. This would not occur until all material in the universe had been combined into one body, or into two bodies in mutual revolution. However, if there are those who say that the universe in action is eternal, through the operation of compensating principles as yet undiscovered, no man of science is at present equipped to prove the contrary.

THE NOVÆ

The so-called new stars, otherwise known as temporary stars or novæ, present interesting considerations. These are stars which suddenly flash out at points where previously no star was known to exist; or, in a few cases, where a faint existing star has in a few days become immensely brighter. Twenty-nine new stars have been observed from the year 1572 to date; 19 of them since 1886, when the photographic dry plate was applied systematically to the mapping of the heavens, and 15 of the 19 stand to the credit of the Harvard observers. This is an average of one new star in two years; and as some novæ must come and go unseen it is evident that they are by no means rare objects. Novæ pass through a series of evolutions which have many points in common; in fact, the ones which have been extensively studied by photometer and spectrograph have had histories with so many identities that we are coming to look upon them as standard products of evolutionary processes. These stars usually rise to maximum brilliancy in a few days: some of the most noted ones increased in brightness ten-thousand-fold in two or three days. All of them fluctuate in brightness irregularly, and usually in short periods of time. Several novæ have become invisible to the naked eye at the end of a few weeks. With two or three exceptions, all have become invisible in moderate-sized telescopes, or have become very faint, within a few months. Two novæ, found very early in their development, had at first dark line spectra, a night later bright lines appeared, and a night or two later the spectra contained the broad radiation and absorption bands characteristic of all recent novæ. After the novæ become fairly faint, the bright lines of the gaseous nebula spectrum are seen for the first time. These lines increase in relative brilliancy until the spectra are essentially the same as those of well-known nebulæ, except that the novæ lines are broad whereas the lines of the nebulæ are narrow. In a few months or years the nebular lines diminish in brightness, and the continuous spectrum develops. Hartmann at Potsdam, and Adams and Pease with the 60-inch Mount Wilson reflector, have shown that the spectra of the faint remnants of four originally brilliant novæ now contain some of the bright lines which are characteristic of Wolf-Rayet stars.[8]

Why the novæ suddenly flare up, and what their relations to other celestial bodies may be, are questions which can not be regarded as settled. Their distribution on the celestial sphere in indicated in Figure 25 by the open circles. In this figure the densest parts of the Milky Way are drawn in outline. All of the novæ have appeared in the Milky Way, with the exception of five: and these exceptions are worthy of note. One of the five appeared in the condensed nucleus of the great Andromeda nebula, not far from its center; another (Z Centauri) was located close to the edge of a spiral nebula and quite possibly in a faint outlying part of the nebula; a third (T Coronæ) was observed to have a nebulous halo about it at the earliest stage of its observed existence; a fourth (τ Scorpii) appeared in a nebula; and the fifth (Nova Ophiuchi No. 2) in 1848 was not extensively observed. The other 24 novæ appeared within the structure of the Milky Way. Keeping the story as short as possible, a nova is seemingly best explained on the theory that a dark or relatively dark star, traveling rapidly through space, has encountered resistance, such as a great nebula or cloud of particles would afford. While passing through the cloud the forward face of the star is bombarded at high velocities by the resisting materials. The surface strata become heated, the luminosity of the star increases rapidly. The effect of the bombardment by small particles can be only skin deep, and the brightness of the star should diminish rapidly and therefore the spectrum change speedily from one type to another. The new star of February, 1901, in Perseus, afforded evidence of great strength on this question. Wolf at Heidelberg photographed in August an irregular nebulous object near the nova. Ritchey's photograph of September showed extensive areas of nebulosity around the star. In October Perrine and Ritchey discovered that the nebular structure had apparently moved outward from the nova, from September to October. Going back to a March 29th photograph taken for a different purpose, Perrine found an irregular ring of nebulosity closely surrounding the star. Apparently, the region was full

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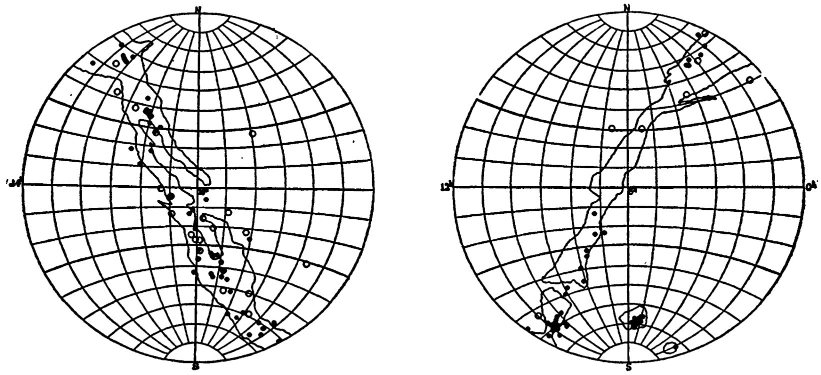
[8] After this lecture was delivered Adams of Mount Wilson reported that in November, 1914, the chief nebular line (5007A) and another prominent nebular line (4363A) had entirely disappeared from the spectrum of Nova Geminorum No. 2, whereas the second nebular line in the green (4959A) remained strong; probably a step in progress from the nebular to the Wolf-Rayet spectrum.

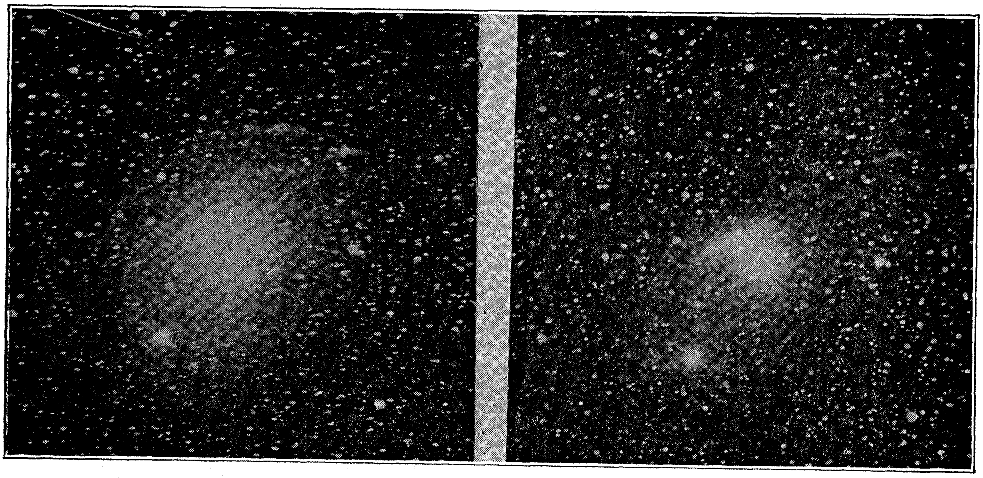


Right Ascension 12^h to 24^h. **Right Ascension 0^h to 12^h.**

O = Novæ. ● = Wolf-Rayet Stars.

FIG. 25. DISTRIBUTION OF NOVÆ AND WOLF-RAYET STARS.

of nebulosity which is normally invisible to us. The rushing of the star through this resisting medium made the star the brightest one in the northern sky for two or three days. The great wave of light going out from the star when at its brightest traveled in five weeks as far as the ring of nebulosity, where, falling upon non-luminous nebulous materials, it made the ring visible. Continuing its progress, the wave of light illuminated the material which Wolf photographed in August, the materials which Ritchey photographed still farther away in September, and the still more distant materials which Perrine and Ritchey photographed in October, November, and later. We were able to see this material only as the very strong wave of light which left the star at maximum brightness made the material luminous in passing. That 24 novæ should occur in the Milky Way, where the stars are most numerous, and where the resisting materials may preferably prevail, is not surprising; and it should be repeated that at least three of the five occurring outside of the Milky Way were located in nebulous surroundings.



November 12 and 13, 1901. January 31 and February 2, 1902.

FIG. 26. APPARENT MOVEMENT OF NON-LUMINOUS NEBULOSITY ABOUT NOVA PERSEI. Photographed at the Lick Observatory.

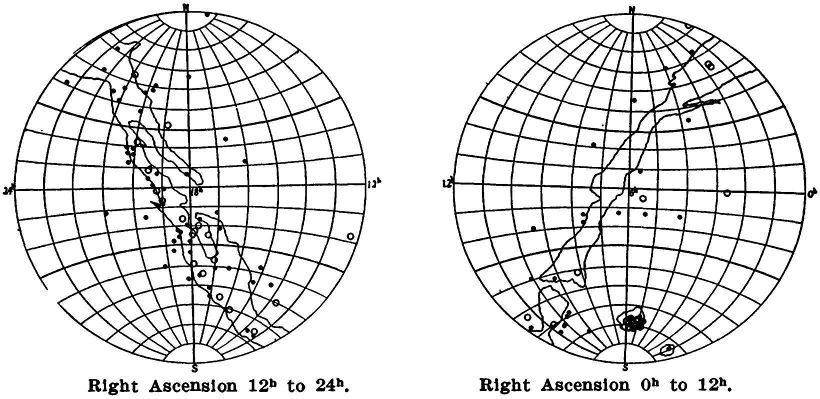
The motion is best shown by the bright mass above and to the right of the center, in comparison with the surrounding stars.

The actual collision of two stars would necessarily be too violent in its effect to let the reduction of brilliancy occur so rapidly as to cause the disappearance of the nova in a few weeks or months. The close approach of two stars might conceivably produce the observed facts, but even this process seems too violent in its probable results. The chances for the collision of a rapidly traveling star with an enormously extended nebulous cloud are vastly greater, and the apparent mildness of the phenomenon observed is in better harmony with expectation.

RELATION OF NOVÆ, PLANETARY NEBULÆ AND WOLF-RAYET STARS

Although all recent novæ have been observed to become planetary or stellar nebulæ, they seem not to remain nebular for any length of time; they have gone further and become Wolf-Rayet stars. Whether any or all of the planetary nebulæ that have been known since Herschel's day, and have remained apparently unchanged in form, have developed from new stars, is uncertain and doubtful. If they have, the disturbances which gave them their character must have been violent, such as would result from full or glancing collisions of two stars, in order to produce deep-seated effects which change slowly, rather than surface effects which change rapidly.

Whether the Wolf-Rayet stars have in general been formed from planetary nebulæ is a different question: some of them certainly have. Wright has recently shown that the stellar nuclei of planetary nebulæ are Wolf-Rayet stars, and he has formulated several steps in the process whereby the nebulosity in a planetary eventually condenses into the central star. The distribution of the planetaries and the Wolf-Rayet stars on the sphere affords further evidence of a connection. We saw that the novæ are nearly all in the Milky Way. The irregular, ring, planetary and stellar nebulæ, plotted in Fig. 27, prefer the Milky Way, but not so markedly. The Wolf-Rayets, without exception, are located in the Milky Way and in the Magellanic Clouds, and those in the Milky Way are remarkably near to its central plane. 107 of these objects are known, 1 is in the Lesser Magellanic Cloud, and 21 are in the Greater Magellanic Cloud. The remaining 85 average less than 2¾° from the central plane of the Milky Way.



Right Ascension 12^h to 24^h. Right Ascension 0^h to 12^h.

FIG. 27. DISTRIBUTION OF GASEOUS (BRIGHT-LINE) NEBULÆ.

● = Ring, Planetary and Stellar. ○ = Irregular.

We are obliged to say that the places of the novæ, of the planetary and stellar nebulæ, and of the Wolf-Rayets in the evolutionary process are not certainly known. If the Wolf-Rayet stars have developed from the planetaries, the planetaries from the novæ, and the novæ have resulted from the close approach or collision of two stars, or from the rushing of a dark or faint star through a resisting medium, then the novæ, planetaries and Wolf-Rayets belong to a new and second generation: they were born under exceptional conditions. The velocities of the planetary nebulæ seem to be an insuperable difficulty in the way of placing them between the irregular nebulæ and the helium stars. The average radial velocity of 47 planetary nebulæ is about 45 km. per second; and, if the motions of the planetaries are somewhat at random, their average velocities in space are twice as great, or 90 km. per second. This is fully seven times the average velocity of the helium stars, and the helium stars in general, therefore, could not have come from planetary nebulæ. The radial velocities of only three Wolf-Rayet stars have been observed, and this number is too small to have statistical value, but the average for the three is several times as high as the average for the helium stars. We can not say, I think, that the velocities of any novæ are certainly known.

If the planetaries have been formed from novæ, especially the novæ which encountered the fiercest resistance, the high velocities are in a sense not surprising, for those stars which travel with abnormally high speeds are the ones whose chances for collisions with resisting media are best; and, further, the higher the speeds of collision the more violent the disturbance. This line of argument also leads to the conclusion that the novæ, planetaries and Wolf-Rayets belong not in general before the helium stars, but to another generation of stars. They may, and I think will, develop into a small class of helium stars having special characteristics; for example, high velocities.

KANT'S HYPOTHESIS

Immanuel Kant's writings, published principally in 1755, are in many ways the most remarkable contributions to the literature of stellar evolution yet made. Curiously, Kant's papers have not been read by the text-book makers, except in a few cases. We have already referred to his ideas on the Milky Way and on comets. In his hypothesis of the origin of the solar system, he laid emphasis upon the facts that the six known planets revolve around the Sun from west to east, nearly in the same plane and nearly in the plane of the Sun's equator; that the then four known moons of Jupiter, the five known moons of Saturn, and our moon revolve around these planets from west to east, and nearly in the same general plane; and that the Sun, our moon and the planets, so far as known, rotate in the same direction. These facts, he said, indicate indisputably a common origin for all the members of the solar system. He expressed the belief that the materials now composing the solar system were originally scattered widely throughout the system, and in an elemental state. This was a half century before Herschel's extensive observations of nebulæ. Kant thought of this elemental matter as cold, endowed with gravitational power, and endowed necessarily with some repulsive power, such as exists in gases. He started his solar system from materials at rest. Most of the matter, he said, drifted to the center to form the Sun. He believed that nuclei or centers of attraction formed here and there throughout the chaotic structure, and that in the course of ages these centers grew by accretion of surrounding matter into the present planets and their satellites; and that in some manner motion in one direction prevailed throughout the whole system. Kant's explanation of the origin of the *rotation* of the solar system is unsound and worthless. We now know that such a cloud of matter, free from rotation, could not of itself generate rotation; it must get the start from outside forces. Kant's false reasoning was due in part to the fact that some of our most important dynamical laws were not yet discovered, in part to his faulty comprehension of certain dynamical principles already known, and probably in part to the unsatisfactory state of chemical knowledge existing at that date. This was half a century before Dalton's atomic theory of matter was proposed.

Kant asserted that the processes of combination of surrounding cold materials would generate heat, and, therefore, that the resulting planetary masses would assume the liquid form; that Jupiter and Saturn are now in the liquid state; and that all the planets will ultimately become cold and solid. This is in fair agreement with present-day opinion as to the planets, save that modern astronomers go further in holding that the outer strata of Jupiter and Saturn, likewise of Uranus and Neptune, down to a great depth, must still be gaseous. In 1785, after the principle of heat liberation attending the compression of a gas had been announced, Kant supplemented his statement of 1755 as to the origin of the Sun's heat. He attributed this to gravitational action of the Sun upon its own matter, causing it to contract in size: he said the quantity of heat generated in a given time would be a function of the Sun's volumes at the beginning and at the ending of that period of time. This is substantially the principle which Helmholtz rediscovered and announced in 1854, and which is now universally accepted—with the reservation of the past ten years, that radioactive substances in the Sun may be an additional factor in the problem.

Kant's paper of 1754 enunciated the theory that the Moon always turns the same face to the Earth because of tidal retardation of the Moon's rotation by the Earth's gravitational attraction; and that our Earth tides produced by the Moon will slow down the Earth's rotation until the Earth will finally turn one hemisphere constantly to the Moon. This principle was in part reannounced by Laplace a half century later, and likewise investigated by Helmholtz in 1854, before Kant's work was recognized.

Kant's speculations on a possible destruction and re-birth of the solar system, on the nature of Saturn's ring, and on the nature of the zodiacal light are similar in several regards to present-day beliefs.

Kant wrote:

> I seek to evolve the present state of the universe from the simplest condition of nature by means of mechanical laws alone.

In 1869 Sir William Thomson, afterwards Lord Kelvin, commented that Kant's

> attempt to account for the constitution and mechanical origin of the universe on Newtonian principles only wanted the knowledge of thermodynamics, which the subsequent experiments of Davy, Rumford and Joule supplied, to lead to thoroughly definite explanation of all that is known regarding the present actions and temperatures of the Earth and of the Sun and all other heavenly bodies.

These are, apparently, the enthusiastic comments resulting from the re-discovery of Kant's papers. A present-day writer would not speak so decisively of them, but we must all bow in acknowledgment of Kant's remarkable contributions to our subject, published when he was but 31 years old.

LAPLACE'S HYPOTHESIS

In 1796, 41 years following Kant's principal contributions, Laplace published an extensive untechnical volume on general astronomy. At the end of the volume he appended seven short notes. The final note, to which he gave the curious title "Note VII and last," proposed a theory of the origin and evolution of the solar system which soon came to be known as Laplace's Nebular Hypothesis. There are several circumstances which indicate pretty clearly that Laplace was not deeply serious in proposing this hypothesis:

1. Its method of publication as the final short appendix to a large volume on general astronomy.
2. He himself said in his note that the hypothesis must be received "with the distrust with which everything should be regarded that is not the result of observation or calculation."
3. So far as we know he did not submit the theory to the test of well-known mathematical principles involved, although this was his habit in essentially every other branch of astronomy.
4. Laplace, in common with Kant, laid great stress upon the fact that the satellites all revolve around their planets from west to east, nearly in the common plane of the solar system; yet 6 or 7 years before Laplace's publication, Herschel had shown and published that the two recently discovered satellites of Uranus were revolving about Uranus in a plane making an angle of 98° with the common plane of the

solar system. While Laplace might not have known of Uranus's satellites in 1796, on account of existing political conditions, there is no evidence that he considered or took note of the fact when making minor changes in his published papers up to the time of his death in 1827. It is a further interesting comment on international scientific literature that Laplace died without learning that Kant had worked in the same field.

Laplace and his contemporary, Sir William Herschel, had been the most fruitful contributors to astronomical knowledge since the days of Sir Isaac Newton. Herschel's observations had led him to speculate as to the evolution of the stars from nebulæ, and as a result interest in the subject was widespread. This fact, coupled with Laplace's commanding position, caused the nebular hypothesis to be received with great favor. During an entire century it was the central idea about which astronomical thought revolved.

Laplace conceived that the solar system has been evolved from a gaseous and hot nebula; that the nebulosity extended out farther than the known planets; and that the entire nebulous mass was endowed with a slow rotation that was *uniform in angular rate,* as in the case of a rotating solid. This gaseous mass was in equilibrium under the expanding forces of heat and rotation and the contracting force of gravitation. Loss of heat by radiation permitted corresponding contraction in size, and increased speed of rotation. A time came, according to Laplace, when the nebula was rotating so rapidly that an outer ring of nebulosity was in equilibrium under centrifugal and gravitational forces and refused to be drawn closer in toward the center. This ring, *rotating as a solid,* maintained its position, while the inner mass contracted farther. Later another ring was abandoned in the same manner; and so on, ring after ring, until only the central nucleus was left. Inasmuch as the nebulosity in the rings was not uniformly distributed, each ring broke into pieces, and the pieces of each ring, in the progress of time, condensed into a gaseous mass. The several large masses formed from the abandoned rings, respectively, became the planets and satellites of the solar system. These gaseous masses rotated faster and faster as their heat radiated into space, they abandoned rings of gaseous matter just as the original mass had done, and these secondary rings condensed to form the satellites; save that, in one case, the ring of gas nearest to Saturn for some reason formed a solid (!) ring about that planet, instead of condensing into one or more satellites. Thus, in outline, according to Laplace, the solar system was formed.

The first half of the nineteenth century found the nebular hypothesis accepted almost without question, but a tearing-down process began in the second half of the century, and at present not much of the original structure remains standing. This is due in small part to discoveries since Laplace's time, but chiefly to a more careful consideration of the fundamental principles involved. We have space to present only a few of the more salient objections.

1. If the materials of the solar system existed as a gas, uniformly distributed throughout what we may call the volume of the system, the density of the gas would be exceedingly low: at the most, several hundred million times less dense than the air we breath. Conditions of equilibrium in so rare a medium would require that the abandonment of the outer parts by the contracting and more rapidly rotating inner mass should be a continuous process. Each abandoned element would be abandoned individually; it would not be vitally affected by the elements slightly farther out in the structure, nor by the elements slightly nearer to the center. Successive abandonment of nine gaseous rings of matter, *each ring rotating as if it were a solid structure,* is unthinkable. The real product of the cooling process in such a nebula would undoubtedly be something in the nature of a spiral nebula, in which the matter would revolve around the nucleus the more rapidly the nearer it was to the nucleus. If the matter were originally distributed uniformly throughout the rotating structure, the spiral lines might not be visible. If it were distributed irregularly, the spiral form here and there could scarcely fail to be in evidence to a distant observer.

2. Laplace held that the condensation of each ring would result in one planet, rotating on its axis from west to east; this apparently by virtue of the fact that in a ring rotating *as a solid* the outer edge travels more rapidly than the inner edge does, and therefore, the west to east direction of rotation must prevail in the planetary product. If now, as we firmly believe, each constituent of such an attenuated ring must rotate substantially independently of other constituents, those nearer the inner edge of the ring will possess the higher speeds of rotation, and the preponderance of kinetic energy in the inner parts of the ring should give the resulting planetary condensation a retrograde direction of rotation.

3. According to Laplace the satellites should all revolve around their primaries from west to east. Eight of the satellites do not follow this rule.

4. If the materials composing the inner ring of Saturn were abandoned by the parent planet, as this planet contracted in size and rotated ever more and more rapidly, then the ring should revolve about the planet in a period considerably longer than the planet period. The reverse is the fact. The rotation period of the equatorial region of the planet itself is 10 h. 14 m., whereas the inner edge of the ring system revolves about the planet once in about five hours.

5. The inner satellite of Mars revolves once in 7 h. 39 m., whereas Mars requires 24 h. 37 m. for one rotation. According to the Nebular Hypothesis, the period of the satellite should be the longer.

6. Laplace's hypothesis would seem to require that the orbits of the planets be circular or very nearly so. The orbits of all except Venus and Neptune are quite eccentric, and Mercury's orbit, which should have the nearest approach to circularity, is by far the most eccentric.

7. If the planetary rings were abandoned by centrifugal action, we should expect the Sun to be rotating in the principal plane of the planet system. The major planets, from Venus out to Neptune, are revolving in nearly a common plane. The Sun, containing $99\frac{6}{7}$ per cent of all the material in the system, has its equator inclined 7° to the planet plane. This discrepancy is a very serious and I think fatal objection to Laplace's hypothesis, as Chamberlin has emphasized.

8. Laplace assumed a nebula whose form was a function of its rotational speed, its gravitation, its internal heat, and, although he does not so state, of its internal friction. He did not distribute the matter within the nebula to conform in any way to the distribution as we observe it to-day, but he let the entire structure contract, following the loss of heat, until the maintenance of equilibrium required the successive abandoning of seven or eight rings. He mentions a central condensation, but gives no further particulars. Thirty years ago Fouché established clearly that the condensing of Laplace's assumed nebula into the present solar system would involve the violent breaking of the law known as the conservation of moment of momentum. Fouché proved that a distribution of matter beyond any conception of the subject by Laplace must be assumed. Fully 96 per cent. must be condensed in the central nucleus *at the outset,* and not more than 4 per cent. of the total mass must lie outside of the nucleus and be widely distributed thoughout the volume of the solar system. Chamberlin puts the case very strongly in another way. If the planet Mercury was abandoned as a ring of nebulosity, the equatorial velocity of the remaining central mass must at that time have been in the neighborhood of 45 km. per second, as this is the orbital speed of Mercury. If the central mass condensed to the present size of the Sun, the Sun's equatorial velocity of rotation should now be fully 400 km. per second, in accordance with the requirement of the rigid law of constancy of moment of momentum. The Sun's actual equatorial velocity is only 2 km. per second!

In several other respects the hypothesis of Laplace, as he proposed it, fails to account for the facts as they are observed to exist.

Poincaré devoted his unique talents to the evolution problem shortly before his death. He recognized that the Laplace hypothesis is not tenable except upon such an assumed distribution of matter as was defined by Fouché. Accepting this modification, and extending the hypothesis to involve the application of tidal interactions at many points throughout the solar system, Poincaré expresses the opinion that the Laplacian hypothesis, of all those proposed, is still the one which best accounts for the facts.[9] However, he does not utilize the hypothesis of rings rotating as solids, for he finds it necessary to conclude that the planetary masses in the beginning must have had retrograde rotations. In the large planetary masses of Jupiter and Saturn, for example, the materials which form the outer retrograde satellites were abandoned while the rotations were still retrograde, and when the diameters of the planetary masses were several scores of times their present diameters. In these extended masses the Sun would create tidal waves, and here, as always, such waves would exert a retarding effect upon the rotations. A time would come, Poincaré thought, when these planets would rotate once in a revolution; that is, present the same face to the Sun; and this is in fact a west to east rotation. Further contraction of the planetary masses would give rise to increasing rotational speeds in the west to east direction. The materials which form the inner satellites of Jupiter and Saturn were abandoned successively after the west to east direction of rotation had become established. According to modifications of the same theory, tidal retardation has slowed down Saturn's speed since the abandonment of the materials which later condensed to form the inner ring of that planet; or, possibly, the ring materials encountered resistance after the planet abandoned them, with the consequence that the ring drew in toward the planet and increased its speed; and similarly in the case of Mars and its inner satellite.

To me this modification of the Laplacian hypothesis is unsatisfactory, for several reasons. To mention only one: if Jupiter was a large gaseous mass extending out as far as the 8th and 9th satellites, the gaseous body was very highly attenuated; friction in the outer strata would be essentially a negligible quantity, and tidal retardation would not be very effective; and it would be under just these conditions that loss of heat from the planet should be most rapid and the rate of increase of retrograde rotation resulting therefrom be comparatively high. It would seem that the rotation of the planet in the retrograde direction must have accelerated under the contractional cause, rather than have decreased and reversed in direction under an excessively feeble tidal cause.

The recognized weaknesses of Laplace's hypothesis have caused many other hypotheses to be proposed in the past half century. The hypotheses of Faye, Lockyer, du Ligondes, See, Arrhenius, and Chamberlin and Moulton include many of the features of Kant's or Laplace's hypotheses, but all of them advance and develop other ideas. It is unfortunate that space limits do not permit us to discuss the new features of each hypothesis.

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[9] Poincaré has made the following interesting comments on Laplace's hypothesis: "The oldest hypothesis is that of Laplace; but its old age is vigorous and for its age it has not too many wrinkles. In spite of the objections which have been urged against it, in spite of the discoveries which astronomers have made and which would indeed astonish Laplace himself, it is always standing the strain, and it is the hypothesis which best explains the facts; it is the hypothesis which responds best to the question which Laplace endeavored to answer, Why does order rule throughout the solar system, provided this order is not due to chance? From time to time a breach opened in the old edifice (the Laplace hypothesis); but the breach was promptly repaired and the edifice has not fallen."

(To be continued.)